[1]W. C. Hahn, Gen. Elec. Rev. No. 42, 258 (1939).
[2]J. R. Pierce, Traveling Wave Tubes (D. Van Nostrand and Company, Inc., New York, 1950), Chap. II, pp. 5-13.
[3]L. Spitzer, Jr., Physics of Fully Ionized Gases (Interscience Publishers, Inc., New York, 1956), Chap. IV, pp. 46-64.
[4]Proceedings of the United Nations International Conference on the Peaceful Uses of Atomic Energy (United Nations, New York, 1958), Vol. 31, pp. 85-92, 134-136, 99-112.
[5]G. H. Joshi, Technical Report, Applied Research Laboratory, Sylvania Electric Products, Waltham, Massachusetts (to be published).
[6]R. Helliwell and T. Bell, Technical Report No. 2, September, 1959, Radioscience Laboratory, Stanford Electronics Laboratory, Stanford University, Stanford, California (unpublished).

HOT ELECTRONS IN METAL FILMS: INJECTION AND COLLECTION

James P. Spratt, Ruth F. Schwarz, and Walter M. Kane
Research Division, Philco Corporation, Philadelphia, Pennsylvania
(Received March 15, 1961)

Studies of electronic phenomena in metals have been made wherein electrons having energies in the range between the Fermi energy and the vacuum level were injected into a metal by quantum tunneling through a thin insulating film. Mead[1] has reported tunnel emission of electrons into a thin metal film in this fashion, where between 0.1 and 0.3 of the emitted electrons were detected by a silicon monoxide-aluminum electrode adjacent to the metal film.

This Letter describes an experiment using a structure in which energetic electrons are injected into a metal, the structure affording an easy method of separating these hot electrons from those around the Fermi level. This experiment provides a convenient way to measure the properties of these hot electrons.

The source of injected electrons is a metal, separated from the base metal into which the electrons are injected through a thin oxide film (see Fig. 1). The electrons can pass through this film only by a quantum mechanical tunneling through the forbidden region. The oxide permits a potential difference V_{EB} to be established between the two metals, and so the electrons arrive in the base metal at an energy approximately qV_{EB} above its Fermi level. The base metal should be thin enough to assure that there is small probability of the electron losing any of this additional energy in a collision in the film. If this condition is met, the electron will arrive at the opposite face of the film qV_{EB} electron volts above the Fermi level. If a second barrier, of height $\phi_C < qV_{EB}$, exists at this face, it will separate the film from a "collector" region. The carrier will pass over this barrier into the collector, and contribute to the current, I_C, in the collector circuit. Lower energy electrons in the metal film, however, cannot surmount ϕ_C, and hence cannot contribute to I_C. Thus, I_C is dependent only upon properties of these hot electrons.

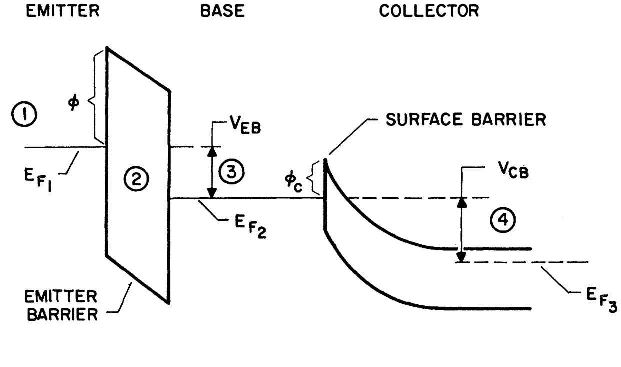

FIG. 1. Electron potential diagram of thin-film structure.

The structure was fabricated as follows: An aluminum film about 100 A thick was evaporated on the etched surface of a 1 ohm-cm, n-type piece of germanium. This created a collector surface barrier at the interface.[2] A thin oxide film was then formed on the surface of the aluminum film. A film of gold was evaporated over the oxide to serve as a source of electrons.

As V_{EB} is increased from zero, the quantum mechanical tunneling of electrons[3] from (1) to (3) occurs (see Fig. 1) and collection can be observed. Figure 2 is a plot at room temperature of I_C vs V_{CB}, and Fig. 3 shows I_C vs V_{EB} for seven different constant values of I_E. These data show low impedance between (1) and (3) indicating that tunneling is occurring, high impedance between (3) and (4) indicating that the

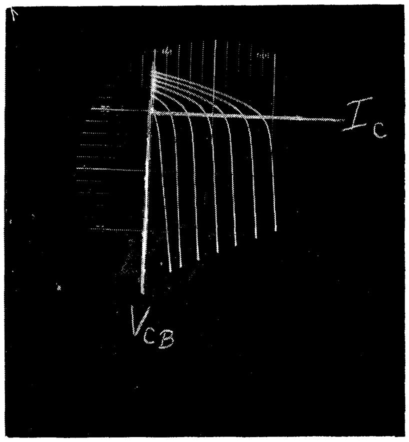

FIG. 2. I_C versus V_{CB} for various values of I_E. Vertical scale: 0.2 volt/division; horizontal scale: 0.5 milliampere/division. $\Delta I_E = 1$ milliampere/step; $T = 300°$K.

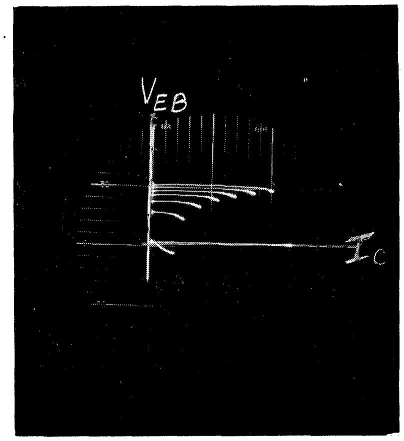

FIG. 3. I_C versus V_{EB} for various values of I_E. Vertical scale: 1 volt/division; horizontal scale: 0.5 milliampere/division. $\Delta I_E = 1$ milliampere/step; $T = 300°$K.

collector is insensitive to low-energy electrons, and a high collection efficiency. About 75% of injected electrons were collected in this experiment. In other experimental structures, up to 90% of the injected electrons have been collected. These data show that the structure can be utilized as an amplifier—similarly to a normal transistor. Furthermore, the geometry employed and the bias configuration preclude the possibility of this effect being due to normal bipolar or analog transistor operation.

Information on scattering processes in the metal film can be deduced from collection efficiency data. For example, if a single collision results in a loss of all the excess energy of an injected electron, then the number of electrons having an excess energy ΔE will vary with distance into the film as

$$n_{\Delta E}(x)/n_{\Delta E}(x_0) = e^{-(x-x_0)/\lambda},$$

where λ = mean free path between collisions.

The 90% collection efficiency quoted above thus implies a mean free path of at least 1000 A. This is significantly greater than the usual numbers quoted for mean free paths of electrons in metals, and suggests that the electrons may undergo many collisions with only a small percentage loss in their excess energy. Even backscattering need not degrade collection efficiency if followed by reflection at the metal-oxide interface. Therefore, the requirements for thicknesses of base metal are not nearly so stringent as one would anticipate from previous data on mean free paths.

Transfer characteristic curves, such as those shown in Fig. 3, also show evidence that reverse biases on the collector influence the current which can pass through the emitter. The effect cannot be explained on the basis of a voltage drop occurring across the lateral base resistance.

Data taken at lower temperatures ($\approx -100°$C) showed a threshold value of V_{EB} of ≈ 0.6 volt before any collection was achieved. This threshold can serve as a direct and accurate measure of the contact potential at metal-semiconductor interfaces.

We wish to thank C. V. Bocciarelli and R. A. Williams for encouragement and support, Dr. Ernest Pittelli for stimulating discussions, Walter Witt for important experimental contributions, and Louis J. Gringeri for fabricating the structures studied.

[1]C. A. Mead, Proc. Inst. Radio Engrs. 48, 359 (1960).

[2]R. F. Schwarz and J. F. Walsh, Proc. Inst. Radio Engrs. 41, 1715 (1953).

[3]R. Holm, J. Appl. Phys. 22, 569 (1951).

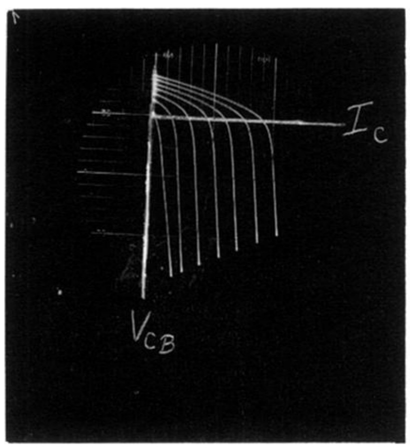

FIG. 2. I_C versus V_{CB} for various values of I_E. Vertical scale: 0.2 volt/division; horizontal scale: 0.5 milliampere/division. $\Delta I_E = 1$ milliampere/step; $T = 300°K$.

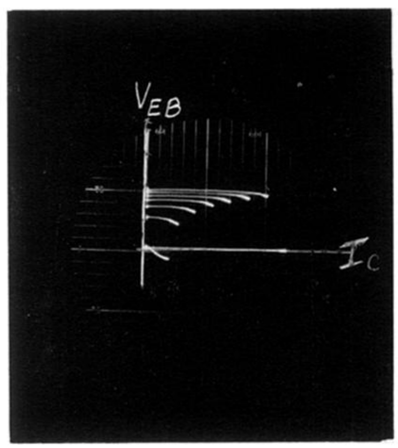

FIG. 3. I_C versus V_{EB} for various values of I_E. Vertical scale: 1 volt/division; horizontal scale: 0.5 milliampere/division. $\Delta I_E = 1$ milliampere/step; $T = 300°K$.